techcommentary

Vacuum Furnaces for Heat Treating, Brazing and Sintering

Introduction

There are a wide variety of electric and fuel-fired furnace types used for materials processing. Each furnace type has advantages and disadvantages depending on the process being conducted. Selection of the furnace type depends on the type and volume of material being processed, the process economics, and the user's preferences. One furnace type gaining increased usage is the electric vacuum furnace (Figure 1). The connected electric load for this type of furnace is typically in the range of 40 kW to 300 kW.

Electrically heated vacuum furnace technology has eliminated environmental problems associated with salt bath furnaces. Electric vacuum furnaces also provide more precise control than traditional gas-fired furnace technology. In addition, more demanding quality requirements for high temperature processing, such as that imposed by the aerospace industry, have pressured the heat treat industry for continuously improved reliability and repeatability. Electric vacuum furnaces can provide this level of quality. Also, the automotive industry's switch to lighter, stronger materials has created a need for higher processing temperatures that are more efficiently accomplished by electric vacuum furnaces. Furthermore, the food and medical instrument industries have become attracted to the "bright" non-oxidized finish on parts heat treated by vacuum furnaces, which eliminates a cleaning step.

Table 1. Industries Using Vacuum Furnaces

SIC	Industry Description
3491	Industrial Valves
3499	Powder Metal Products
3533	Oil and Gas Field Machinery
3544	Cutting Tools and Dies
3556	Food Products Machinery
3714	Motor Vehicle Parts
3724	Aircraft Engines
376	Aerospace
3841	Surgical and Medical Instruments

Applications

Applications for these high-temperature electrically heated vacuum furnaces include:

- Hardening
  - Tool Steels
    - Chromium, Tungsten, and Molybdenum hot-work steels (H series)
    - Tungsten and Molybdenum high-speed steels (T and M series)
- Annealing
  - Stainless Steels
    - Conventional, Stabilized, Low-carbon, and High-nitrogen grades
  - Nickel Alloys
    - Inconels and Hastelloys
- Solution Treating
  - Superalloys
    - Iron-base, Nickel-base, and Cobalt-base
- Brazing
  - Base metals containing more than a few percent of aluminum, titanium, zirconium, or other elements with particularly stable oxides.
- Sintering
  - Tungsten Carbide
  - Metal Injection Molding
  - Ceramics

These applications are found in the industries listed in Table 1.

Figure 1. Vacuum Furnace Setup

Process Fundamentals

The process of vacuum heat treating begins with the placement of the workpieces in a basket or on a platen table. The basket or table is lifted into the furnace and placed onto the furnace hearth using a forklift or integral gantry system. The furnace door (or bottom of the furnace) is then closed and the air in the chamber is evacuated using vacuum pumps. The temperature of the workpieces is raised by the heating elements to the prescribed level during the ramp-up phase (Figure 2). This process temperature is held for some period of time to allow the energy radiated to the part surface to conduct throughout the workpiece (to achieve equilibrium temperature) and to facilitate metallurgical changes which are time dependent. After "soaking" at this high temperature, the workpiece temperature is rapidly decreased in a process phase known as quenching. A wide range of metallurgical properties of the workpiece can be achieved with small variations in the temperature-time profile during quenching. After quenching is complete, workpieces are often subjected to a second heating and cooling cycle at a considerably lower temperature to temper the workpiece. Tempering results in a trade off of one desirable material property (say, increased toughness) with another material property (say, decreased strength).

Essential aspects of the heat treating of metals include controlling the uniformity of temperature from the surface to the center of the part and protecting the surface of the metal at high temperatures by controlling the surrounding atmosphere. A temperature profile that is not uniform within a part can cause cracking from thermal shock or distortion stresses. Nonuniform temperature also can result in nonuniform transformation of the metal and, thus, nonuniform properties of the metal throughout the part. Improper protection of the part surface can result in a buildup or scale that must be mechanically or chemically removed in a subsequent operation after heat treatment. Certain atmospheres at high temperatures can also leach out metal alloying elements such as carbon from the part surface.

Technical Considerations

The primary components of a vacuum furnace include the exterior chamber, the hot zone, work-holding fixtures, heating elements, vacuum pumps, controls, and a quenching system. The exterior chamber surrounds the hot zone, fixtures, heating elements, and, sometimes, the quench blower fan. The quenching system rapidly lowers the temperature of heated parts using inert gas flow. The hot zone concentrates the heat on the workpieces and away from the chamber wall.

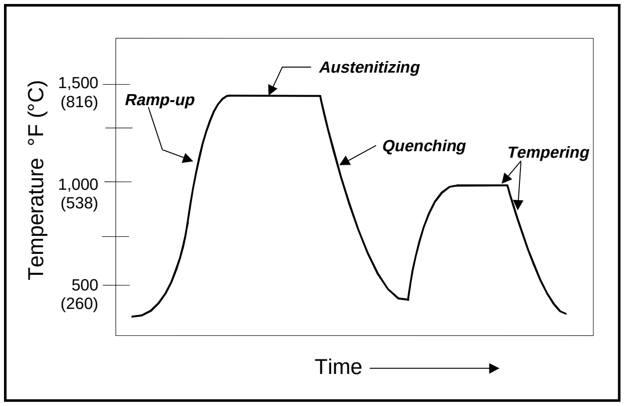

Figure 2. Heat Treating Temperature Profile

Chamber Design

Vacuum furnaces are available for workloads from several pounds to hundreds of tons. Chamber sizes range from 1 ft^3 (0.028 m^3) to hundreds of cubic feet. Vacuum furnaces can be grouped into one of three basic designs:

- Horizontal-loading, or box furnaces (Figure 3)
- Top-loading vertical, or pit furnaces
- Bottom-loading vertical, or bell furnaces

Horizontal loading designs are usually cylindrical shells with hinged circular convex doors on each end sealed by O-rings. Many of these furnaces are equipped with special lifting and transfer forks permanently aligned with the chamber. Some horizontal-loading designs incorporate multiple chambers designed to internally transfer workloads (Figure 4). The conveyor, walking beam, roller-hearth, and pusher-type furnace designs can be adapted for vacuum furnaces. Vertical furnaces are preferred when long and slender parts (that would distort from gravity) are inserted or to facilitate large, heavy loads.

Chamber Insulation

Hot-wall vacuum furnaces were the first chamber type to be designed. Heating elements inside a refractory insulated chamber surround a vacuum-tight retort in which the parts are placed. Slow heating and cooling capabilities relegate this design to temperatures below 1,800°F (980°C), similar to gas-fired vacuum furnaces.

Cold-wall vacuum furnaces incorporate water-cooled coils on the furnace wall and doors (Figure 5). The temperature of the external vessel is maintained near ambient, allowing large units to be constructed since the vessel strength is

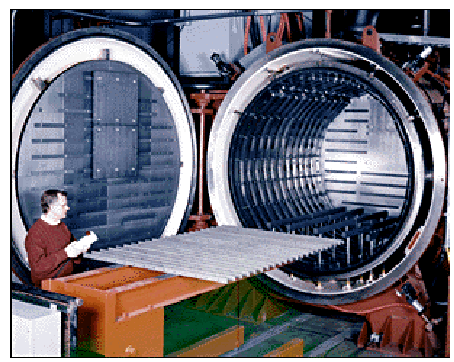

Figure 3. Horizontal Vacuum Furnace

Heat Treating

Heat Treating is a process in which metal is heated and cooled under tight controls to improve its properties, performance, and durability. Heat treating may be used for a variety of purposes, it can

- Soften the metal to improve formability (annealing and stress relieving)
- Make a part harder (austenitizing followed by quenching) to withstand tough service
- Increase the part strength (solution treating followed by precipitation or aging)
- Put a hard surface on relatively soft components (case hardening) to increase abrasion resistance
- Toughen brittle parts (tempering).

Brazing & Sintering

Brazing joins metals by heating them in the presence of a filler metal having a melting temperature above 840°F (450°C), but below the melting temperature of the base metals being joined. The filler metal distributes itself between the closely fitted surfaces of the joint by capillary action. Parts made by compacting metal powder followed by thermal processing (sintering) are called powder metal parts. Sintering is the process wherein compacted powder particles develop metallurgical bonding and further densify under the influence of high temperatures (below the melting temperature of any constituent in the material).

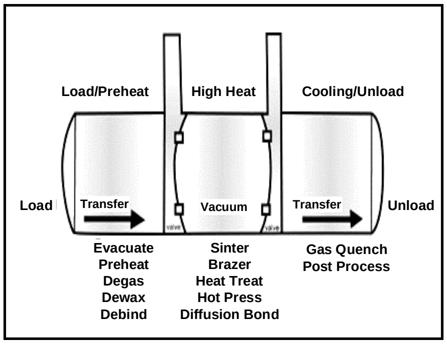

Figure 4. Multiple Chamber Vacuum Furnace

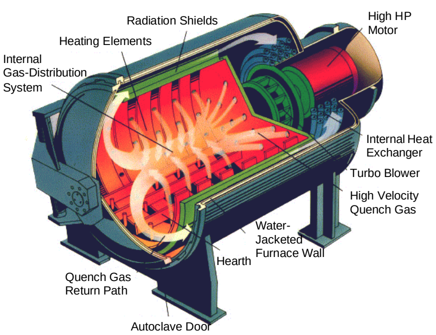

Figure 5. Cold-wall Vacuum Furnace

not compromised. In addition, the vacuum itself acts as an insulator because the thermal conductivity of a vacuum is essentially zero.

Hot Zone

The hot zone in a furnace surrounds the heating elements and the hearth assembly on which parts are placed (Figure 6). It keeps the heat concentrated on the parts and away from the chamber wall. Hot zones are either an "all-metal" or "radiation shield" design or an "insulated type" design. Insulated hot zones are usually rectangular boxes constructed with a rigid graphite board, a graphite-felt material, or a combination of board and felt. Insulation materials, by their very nature, are hygroscopic (i.e. they absorb water) and therefore limit vacuums to a reduced level. Although they are energy efficient, insulation materials do not readily give up heat and limit quenching rates.

All-metal hot zones consist of multiple concentric layers of thin, heat-resisting sheet metal that reflects energy back into the hearth. The vacuum in the chamber prevents loss by convection and permits the use of multiple radiation shields of very low mass. The advantages of all-metal hot zones include:

- Maximum quench rates
- Ultra-high achievable vacuum levels
- Excellent temperature uniformity
- Faster heating rates (due to their high ratio of radiating surfaces)
- Accelerated pump-down rates, and
- Titanium processing ability (no carbon contamination concerns from graphite insulation).

Pure molybdenum is the most widely used refractory metal for hot zones. However, pure molybdenum components recrystallize after the first process run and grain growth takes place, making them susceptible to physical damage due to loss of ductility. In addition, pure molybdenum deteriorates upon contact with "dripping" nickel braze alloy run-off. Alternative molybdenum alloys include Titanium Zirconium (TZ) and Molybdenum-Lanthanumoxide (ML) alloys with higher recrystallization temperatures and higher strength. One powder metallurgy product, PM2000, is an oxide-dispersion-strengthened (ODS) superalloy that offers advantages for furnace brazing applications.

Fixtures

The workload in most vacuum furnaces is placed on a tray or in a basket made from molybdenum, austenitic stainless steel, or Inconel. The work-supporting tray usually rests on a graphite or metallic hearth consisting of three or four horizontal bars supported by piers rising from the furnace shell below. It is essential that metallurgical reactions between the hearth and the work tray/basket be taken into consideration. Thin sheets or tubes of ceramic material are often used to separate the fixtures.

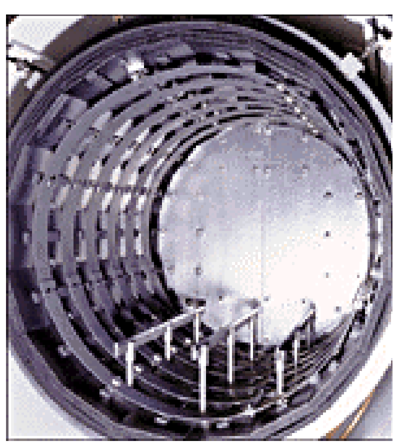

Figure 6. All-metal Hot Zone

Heating Elements

Heating elements must not deteriorate at high temperatures, must radiate considerable amounts of energy, and must be easily replaced. Heating element materials for high temperature vacuum furnaces include refractory metals (tungsten, molybdenum, and tantalum) and pure graphite (solid bar or woven cloth) as shown in Figure 7.

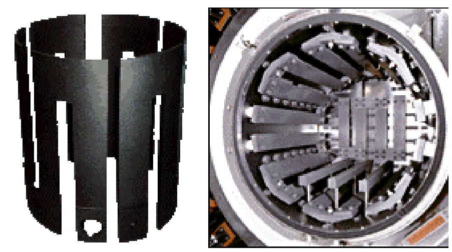

Figure 7. Heating Elements

Molybdenum is the most widely used refractory metal element and undergoes a large increase (500%) in electrical resistivity between room temperature and normal operating temperatures. Tungsten is capable of withstanding higher operating temperatures. Graphite is less expensive than metallic resistors and has up to a 20% decrease in electrical resistivity as it heats. Low voltage (generally, <70 volts) power supplies are normally used because a high electrical potential can produce short-circuiting of the elements by ionizing the residual gases in the chamber. Rated power ranges from 40 kW to 300 kW.

Vacuum Pumps

Pumping systems are usually divided into two subsystems: the roughing pump and the high-vacuum pump. Pumps are classified as mechanical, diffusion, or cryogenic types and are often used in combination. The vacuum system shown in Figure 8 consists of a diffusion pump which is initially isolated from the mechanical roughing/forepump by closing both the high-vacuum valve and foreline valve. When the chamber pressure is sufficiently low, the roughing valve is closed and the other two valves opened to allow the diffusion pump to achieve the final vacuum level.

The level of vacuum achieved can be stated in several different units of measure. The standard absolute pressure of the atmosphere can be expressed in the following units:

1 atm = 760 torr = 760 mm Hg (height of a mercury column)
= 29.21 in. Hg
= 14.696 psia
= 1 x 105 Pa

The general range of vacuum achieved for vacuum furnaces is shown in Table 2 below.

Table 2. Vacuum Ranges for Furnaces

Vacuum Level	Torr	kPa
Rough	750 to 1	100 to 1.3×10^{-1}
Soft	0.1 to 10^{-3}	1.3×10^{-2} to 1.3×10^{-4}
Hard	10^{-4} to 10^{-6}	1.3×10^{-5} to 1.3×10^{-7}

Mechanical pumps are positive-displacement pumps that use pistons or rotating vanes to compress and expel air. Oil-sealed rotary mechanical pumps can achieve a soft vacuum of 0.025 torr (3.3×10^{-3} kPa) (25 µm Hg). A rotary vane booster pump connected upstream from a rotary piston pump can achieve a vacuum of 0.01 torr (1.3×10^{-3} kPa). Oil vapor diffusion pumps can achieve a hard vacuum of 10^{-4} torr (1.3×10^{-5} kPa). To achieve the highest vacuum level (10^{-6} torr) (1.3×10^{-7} kPa), a cryogenic pump is used in combination with a mechanical forepump.

Oil vapor diffusion pumps allow air molecules to randomly diffuse into the throat of the pump where a preferred direction of motion is imparted by momentum transfer. The diffusion pump consists of a boiler for vaporizing special highly stable liquids with very low vapor pressure, concentric vapor chimneys that rise out of the boiler, and a water-cooled pump housing. Vaporized pump oil is sent up the chimneys and then abruptly ejected downward by the chimney nozzles. Molecules from the vacuum chamber are caught in the downward stream of heavy oil molecules and directed to the mechanical forepump. Pump vapor is condensed on the cooled inner walls and is returned to the boiler. Cryogenic pumps condense gas molecules on refrigerated surfaces at -320°F (-195°C). These pumps are regenerated periodically by heating the condensing surfaces to vent the accumulation of condensed gases.

Process Control Instrumentation

Recent advances in vacuum furnace technology have been most apparent in process control instrumentation. The trend is to use "open architecture" personal computer-based software rather than proprietary hardware to control industrial processes such as heat treating. Temperature sensing is usually accomplished by thermocouples made from nickel molybdenum, platinum rhodium, or tungsten-rhenium. Pressure sensing is accomplished by measuring a physical characteristic of the gas that bears a direct relationship to the pressure (e.g. thermal or electrical conductivity). Proportioning controllers are used to bring the parts up to temperature and avoid temperature overshoot due to the thermal inertia of the furnace and parts. The proportioning controller responds to an error signal comparison (set-point vs. actual) by considering the size of the error signal (Proportional band or gain), the error signal size plus the length of time it has existed (Integral reset), and the error signal speed of change (Derivative rate). Thus, the controller is often referred to as a PID, or three mode, controller.

Quenching

Rapidly lowering the temperature of heated parts by contact with a quenchant is just as important as the method of heating. The trend is to replace quenching in liquid media (salt baths, oil, water, etc.) by inert gas quenching. Increasing quench gas pressure is more cost effective than increasing gas flow to achieve higher cooling rates. Another trend is to use gas blends of either nitrogen or argon with helium at increasingly higher pressures. The relative cooling rates and cost of hydrogen, helium, nitrogen, and argon are plotted in Figure 9. For a given furnace, blower, and gas pressure, helium will cool a given workload twice as fast as nitrogen but is eleven times as expensive!

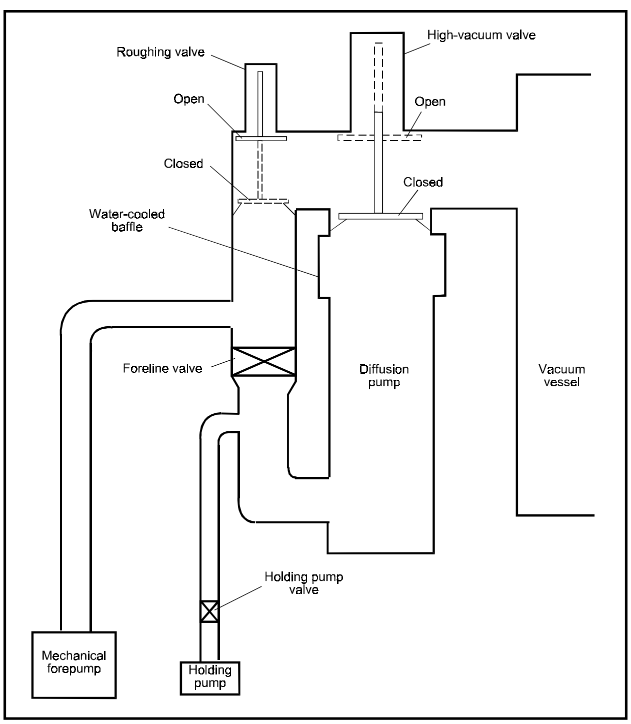

Figure 8. Typical Vacuum System

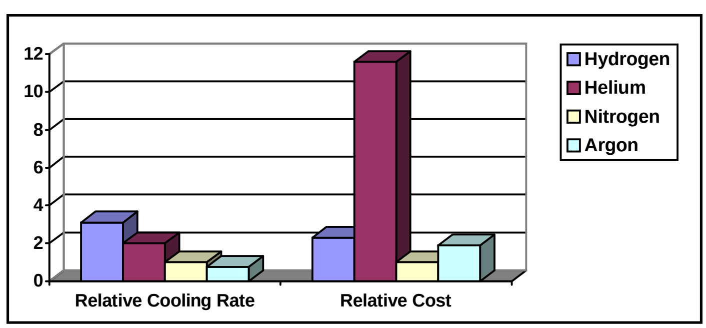

Figure 9. Effect of Gas Type on Relative Cooling Rate and Costs

Quenching in high temperature vacuum furnaces is accomplished by backfilling the chamber with an inert gas to promote the convective transfer of heat from the parts. There are three primary factors that govern heat transfer in vacuum furnaces: the gas cooling or heat transfer coefficient, *H*; the difference between the temperature of the load and the recirculated gas; and the surface area of the load exposed to the gas. Quenching gas is recirculated through a water-cooled heat exchanger. The temperature difference and surface area factors remain almost constant for a specific application. The cooling coefficient is a measure of the rate of heat removal per unit area per degree of temperature. It is proportional to the gas type, quench pressure and blower horsepower (an indirect approximate of gas velocity).

Relative values of heat transfer coefficient (*H*) for various gas blowers (in horsepower) are shown in Table 3. If all other factors for a given furnace are constant, doubling fan power will increase cooling performance by roughly only 20%. Changing from one cooling gas to another, however, also necessitates a change in the blower fan to maintain a constant horsepower. For example, a furnace backfilled with helium instead of nitrogen would only load the blower to 14% of full current. The net effect would be an improvement of only 25% in cooling performance rather than 200%.

A doubling of gas quench pressure will boost cooling performance by about 40%. Quenching systems with 2, 4, 6 and 10 bar pressures (200, 400, 600, and 1,000 kPa) are readily available. One bar (100 kPa) is slightly less than one standard atmosphere of absolute pressure.

Table 3. Effect of Blower Horsepower on Cooling Coefficient

Blower power, hp (W)	Relative cooling coefficient, H
50 (37,300)	0.85
100 (74,600)	1.0
150 (111,900)	1.1
200 (149,200)	1.2
300 (223,800)	1.3

Systems with 20 bar (2,000 kPa) capability are just starting to appear. Helium-argon or helium-nitrogen mixtures are routinely used by a growing number of heat treaters. Hydrogen gas is explosive and must be used with extreme care.

Advantages

Vacuum furnaces remove almost all of the components associated with normal atmospheric air (O_2, N_2, and water vapor) from the heating chamber before and during heating, thus offering the following advantages compared to non-vacuum furnaces:

- Almost complete removal of oxygen and water vapor
- Extraction of deleterious gases, surface contaminants, and processing lubricants
- Achieving a vacuum is often faster than purging with inert gases

The advantages of an electrically heated vacuum furnace compared to gas-fired vacuum furnaces include:

- Much more energy efficient at high temperatures
- More precise ramp-up and cool-down temperature control

Electric vacuum furnace processing is also helping to achieve long-term industry goals. The heat treating industry's desire for the future was published by ASM International as the *Heat Treating Industry Vision 2020* which included the following industry goals:

- Reduce energy consumption by 80%
- Approach near zero emissions
- Reduce production costs by 75%
- Reduce processing times by 50%

Vacuum furnace processing has improved performance in each of these areas compared to gas-fired furnaces.

Competing Processes

The higher the temperature of a metal, the more sensitive it is to reacting with the atmosphere around it. Direct fuel-fired furnaces require a supply of oxygen in the heating chamber to support combustion and introduce water vapor into the chamber. An atmosphere with oxygen promotes oxidation (corrosion, rusting and scaling), tarnishing, and decarburization of ferrous alloys heated to elevated temperatures. Indirect-fired gas furnaces using a *muffle/retort* can incorporate a neutral atmosphere of nitrogen gas to protect the workpiece, but heat transfer is uneven and inefficient, especially at high temperatures.

The greatest growth in applications for vacuum furnaces is coming from hardening, brazing, and sintering applications above 1,800°F (980°C). The energy efficiency of gas-fired furnaces decreases rapidly at temperatures above 1,800°F (980°C), significantly increasing operating costs.

Salt baths are still considered competition to vacuum heat treating. A number of heat treaters have invested in up-grading their salt bath installations to comply with current EPA/OSHA requirements. This is due mainly to the reluctance of job shop customers to invest in the research necessary to prove to themselves that a switch of technology will not adversely affect their parts. Salt bath technology is still useful for some applications, however, each year fewer and fewer salt baths remain in operation.

Fluidized-bed furnaces offer another method of high-temperature heat treatment. This method uses a solid rather than a liquid or gas for the heat transfer medium. The furnace is composed of a layer of permeable particles of an inert refractory (aluminum oxide or silica sand) in a container that is heated and agitated by a flowing stream of gas. The gas flow lifts the particles and imparts to them a violent turbulent motion. Although the particles are actually solid, the fluidized bed simulates the motion of a liquid. Heat is transferred from the particles to an immersed object at a rate two to ten times higher than provided by normal convection or radiation. The heat source can be gas or electric.

Economic Considerations

The following example calculates the total cost (excluding overhead and maintenance) for vacuum annealing at a soak temperature of 1,900°F (1038°C). Tables 4, 5, and 6 show the specifications used for this calculation.

The total cost for this example is shown in Table 7 below. Note that no overhead is included in the labor cost and no routine maintenance costs are included. In this example, the $37.30 total electric power cost represents nearly 25% of the total fixed plus variable costs to operate this vacuum furnace for heat treating.

Summary

High temperature (>1,800°F or 980°C) vacuum furnaces are an excellent replacement for salt bath heat treating, brazing, and sintering applications. Gas-fired furnaces cannot operate efficiently at these high temperatures. Electric power costs can represent one-fourth to one-third of the total costs to operate a vacuum furnace for heat treating. Once installed, vacuum furnaces are increasingly utilized for treating parts previously processed by gas-fired furnaces. Electric vacuum heat treating furnaces also contribute to meeting the long term goals of the heat treating industry.

Sources used in this issue of *TechCommentary* were:

ASM Handbook, *Heat Treating*, Volume 4, 1991.

George C. Carter "Optimizing Gas Quenching." *Advanced Materials and Processes*, February 1996.

A. Bruce Craven "Energy Dominates in Job Costing for Vacuum Furnaces." *Industrial Heating*, February 1996.

Klaus H. Hemsath "Heat-treating in the 21st Century - the Role of Gas-Fired Vacuum Furnaces." *Metallurgia*, January 1999.

Thomas P. Farrell "Technically Advanced Materials for Vacuum Furnace Hot Zones." *Metallurgia*, March 1998.

Table 4. Vacuum Annealing Equipment Specifications

225 kW hot zone power supply capacity
20 hp mechanical pumping motor
75 hp gas recirculating fan motor
7.5 hp vacuum booster motor
18 kW diffusion pump heater
2 kW isolation transformer for controls
Total electric load = 322 kW (1 hp = 0.75 kW)

Table 5. Vacuum Annealing Process Specifications

20°F (11°C)/minute heating ramp @ 80% capacity
300 CF quench gas volume requirement
1/2 hour soak time
2 hour quench with nitrogen

Table 6. Vacuum Annealing Cost Specifications

$350,000 installed cost for furnace
$0.06/kWh electricity cost (1 hp = 0.75 kW)
$15/hr direct labor rate (no overhead)
$0.55/100 scf for nitrogen gas
$20,000 fixtures cost over 5 years
$75,000 hot zone replacement every 4 years

Table 7. Total Cost for Vacuum Annealing Cycle (4 hr)

Furnace ($12.65/hr* x 4 hr)		$50.60
Electric:	Heat-up	16.20
	Soak (hold)	3.40
	Quench (cool)	6.75
	Various components	10.95
Direct Labor		45.00
Process Gas		2.75
Fixtures, baskets, grids		3.50
Water System		1.00
Hot Zone ($4.15/hr* x 4 hr)		16.60
TOTAL		$156.75

*Installed cost financed over 4-7 years at 10% interest rate

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